

EVALUATING THERMALLY DAMAGED POLYIMIDE INSULATED WIRING (MIL-W-81381) WITH ULTRASOUND

Eric I. Madaras

NASA Langley Research Center
Nondestructive Evaluation Sciences Branch
NASA, Hampton, VA 23681

Robert F. Anastasi

U.S. Army Research Laboratory
Vehicle Technology Directorate, AMSRL-VT-S
Nondestructive Evaluation Sciences Branch
NASA Langley Research Center, Hampton, VA 23681

ABSTRACT

A series of experiments to investigate the use of ultrasound for measuring wire insulation have been conducted. Initial laboratory tests were performed on MIL-W-81381/7, /12, and /21 aviation wire, a wire that has polyimide (Kapton®) layers for insulation. Samples of this wiring were exposed to 370°C temperatures for different periods of time to induce a range of thermal damage. For each exposure, 12 samples of each gauge (12, 16, and 20 gauges) were processed. The velocity of the lowest order axisymmetric ultrasonic guided mode, a mode that is sensitive to the geometry and stiffness of the wire conductor and insulation, was measured. The phase velocity for the 20-gauge MIL-W-81381/7 wire had a baseline value of 3023 ± 78 m/s. After exposure to the high temperatures, the wire's phase velocity rapidly increased, and reached an asymptotic value of 3598 ± 20 m/s after 100 hours exposure. Similar behavior was measured for the 16 gauge MIL-W-81381/21 wire and 12 gauge MIL-W-81381/12 wire which had baseline values of 3225 ± 22 m/s and 3403 ± 33 m/s respectively, and reached asymptotic values of 3668 ± 19 m/s, and 3679 ± 42 m/s respectively. These measured velocity changes represent changes of 19, 14, and 8 percent respectively for the 20, 16, and 12 gauge wires. Finally, some results for a wire with an ethylene tetrafluoroethylene insulation are reported. Qualitatively similar behaviors are noted ultrasonically.

INTRODUCTION

Electrical wiring is subjected to heat, cold, moisture, strain and vibrations, which eventually causes damage to the wire insulation and can lead to the wire conductor failure. In most cases these environmental and operational conditions are modest and wiring is used safely for years, but in the case of aerospace and aeronautics usage, these conditions are more extreme and can cause the insulation to chafe, to become brittle and to crack prematurely, sometimes with serious consequences. The common practice to deal with wiring faults is often after-the-fact, usually done in response to an instrument or system failure. In those cases, wire inspections are done visually and find the obvious cracks, damage, and burns. However, visual inspections give little quantitative information about the condition of the wire-insulation prior to wire failure or the condition of

visually intact wire which is near critical failure.

In its basic geometry the insulated wire may be considered a cylindrical clad wave-guide, where the wire conductor is the core and the wire insulation is the cladding. A number of researchers have examined acoustic guided wave propagation in cylindrical geometry [1-4]. some applications of ultrasonic guided waves include material testing or characterization of wire and fibers and use as ultrasonic delay lines [5, 6]. Preliminary ultrasonic testing of wiring has suggested the efficacy of this concept as it is applied to electrical wiring [7, 8].

In general many acoustic wave modes will propagate in an isotropic cylinder. The lowest order modes of vibration are the axial symmetric modes, which can be divided into axial-radial and torsional modes. The next order mode of vibration is the flexural mode and higher modes are screw modes [2]. Figure 1 shows for a 1/8" brass rod the lowest branch of the axial-radial mode extending to zero frequency where the limiting phase velocity is called the bar velocity in the simple isotropic case, and is related to the Young's modulus of the material. In the low frequency regime this mode is nearly non-dispersive. As the frequency is increased the phase velocity drops and then asymptotically approaches the rayleigh velocity at higher frequencies. Figure 1 also shows the first flexural mode's dispersion behavior which is characterized by a zero phase speed at zero frequency. As the frequency increases, the phase velocity increases. It asymptotically approaches

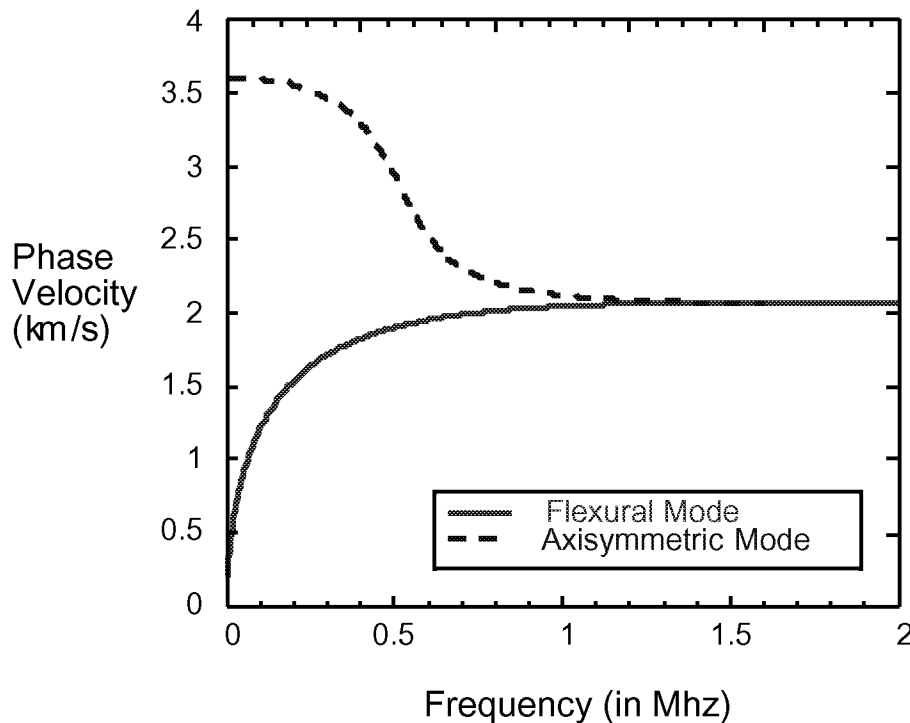


Figure 1: The phase velocity of the first axisymmetric wave mode and the first flexural wave mode of a solid 1/8" brass cylinder.

the axisymmetric wave speed from below.

The addition of a layer of polymer insulation has a significant effect on the two low order modes as seen in Figure 2. In that figure, the calculation is for a 1/8" brass rod with a layer of polyolefin plastic. The effect is to lower the frequency range where dispersion is most noticeable and to lower the phase velocity. The low frequency axisymmetric wave velocity drops about 20% in this instance and the high frequency asymptotic limit is related to the plastic's properties rather than the brass' properties.

To investigate the concept of using guided waves for insulation assessment, a series of experiments were conducted. The first test was to evaluate consistency of theory and a simple model consisting of a solid cylinder and then a solid cylinder coated with a polymer. Several guided modes were generated and their character were compared with modeling results. Next, a series of aviation grade wiring was tested to evaluate their ultrasonic properties. Some of the wiring, designated as MIL-W-81381 wiring, is insulated with polyimide layers. This wiring is commonly referred to as Kapton® wiring which has been identified as an aging wiring that can fail prematurely under certain conditions. Another test set was a wiring type with a modified ethylene-tetrafluoroethylene (E-TFE) insulation (designated as MIL-W-22759/34) which is also used in aircraft. The conductors for these materials have a stranded conductor construction rather than the solid cylindrical form of our initial model and the insulation can be wrapped rather than a contin-

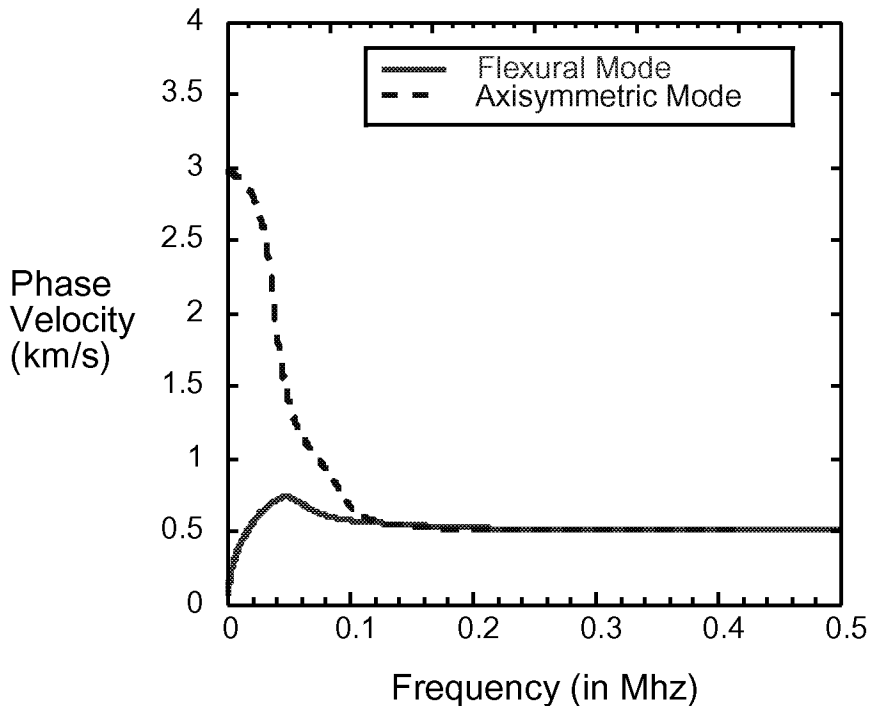


Figure 2: The phase velocity of the first axisymmetric wave mode and the first flexural wave mode of a solid 1/8" brass cylinder with a layer of insulation.

uous cylinder, and thus it is important to evaluate the character of the ultrasound signal to see if it also followed the simple model or if a new model would be necessary. These wires were exposed to high temperatures for various times to create wires with various conditions.

EXPERIMENT

The experimental system used is shown in Figure 3 and consisted of an ultrasonic spike generation pulser to generate the ultrasonic waves. Two similar longitudinal wave transducers were used in a pitch catch mode for generation and reception. The transducers were low frequency, broadband, acoustic emission transducers with a bandwidth of 50 KHz to 2 MHz. On reception, a 20 KHz to 2 MHz pre-amplifier with 40 or 60 dB of switchable gain fed into an amplifier with a maximum of 42 dB of gain and with the bandwidth set at 10 KHz to 300 KHz. The output of the amplifier was recorded by an 8-bit/500 MHz digitizing oscilloscope. That signal was averaged 1000 times. Two hundred μ secs of signal were recorded.

the transducers were mounted in simple sample holders that could be clamped to a wire. The transducer holder was designed to hold the wire across the center of the transducer's face. For this work, the wires were mounted on a 30 cm long optical rail with spacings marked off in millimeters. The spacing of the transducers was adjusted from 3 cm to 29 cm to measure a range of arrival times and spacings. The wire samples were nominally 60 cm long. For the case of measuring the phase velocity, the first arrival peak of the signal at each distance was used to estimate a velocity. A least squares routine was used to calculate the velocity and to estimate the error of the velocity from the distance versus time data.

To generate the thermal damage in wiring, the wire were placed in a large laboratory oven with a maximum operating temperature of 400°C. Sets of 12 wires were placed in the oven and heated to 370°C for the Kapton® wires and to 270°C for the E-TFE insulated wires. The general heating curves are shown in Figure 4. The ovens were able to reach the dwell temperature in about an hour. The cool down period lasted longer. For the wires that were tested, sets of each wire type

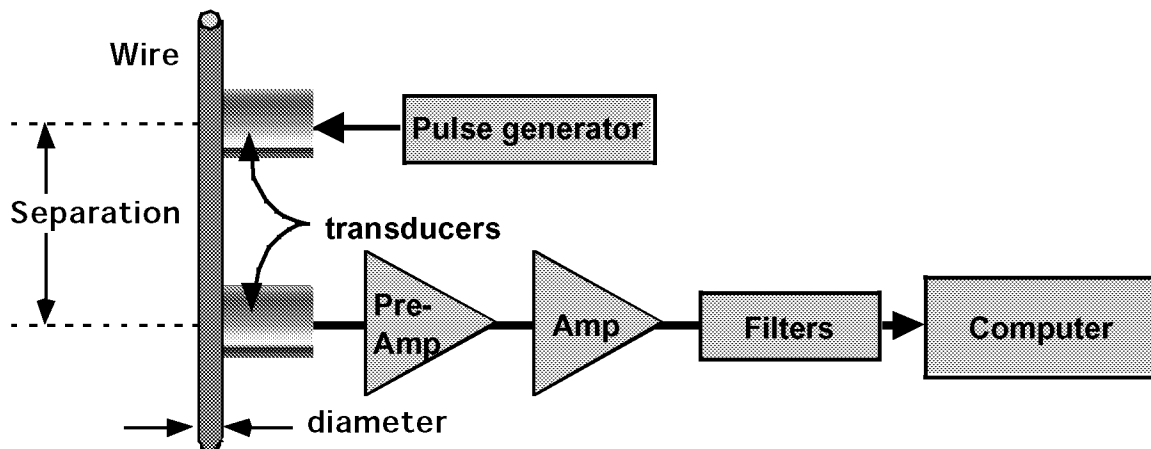


Figure 3: Experimental set up.

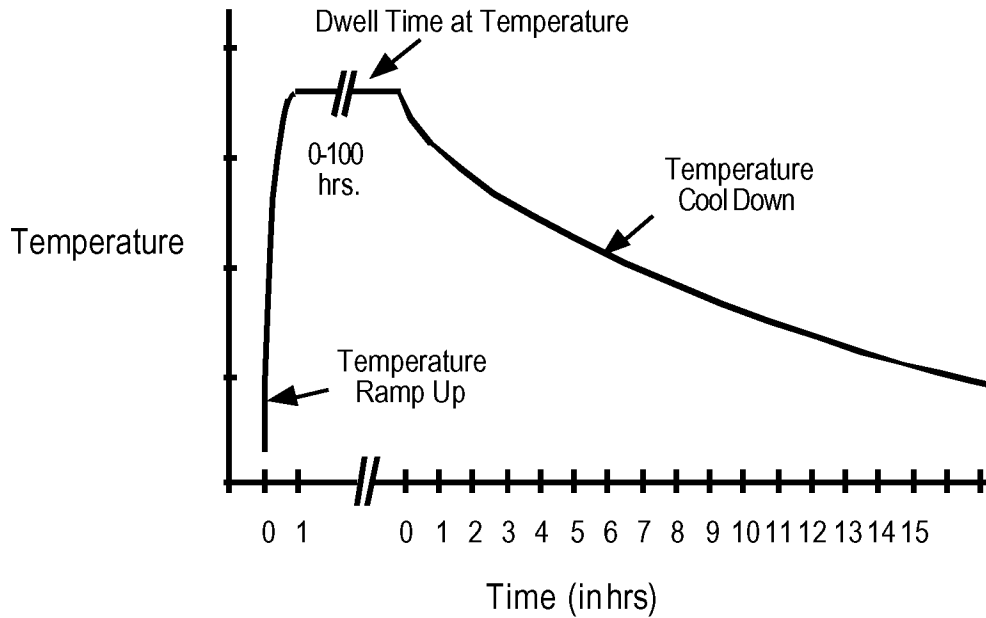


Figure 4: Thermal protocol for heat damaging wire insulation.

and size were heated to their dwell temperature for 0, 3, 6, 9, 12, 15, 20, 30, 40, or 100 hours. These wires were subsequently measured with the apparatus previously described.

RESULTS

Solid Insulated Wire Model. Initial measurements were carried out on a simple model of an insulated wire to identify various wave modes. This model consisted of a solid aluminum rod with and without a polymer coating. The aluminum rod, simulating the wire, had a 3.23 mm diameter. The polymer coating, simulating the insulated wire had a thickness of 0.57 mm. The coating was a thermoplastic heat-shrink material of polyolefin. Published density and modulus of this material is 0.971 gm/cm^3 and 1.2 GPa respectively, and the measured longitudinal wave velocity is 1870 m/s. [9] The final diameter of the model was 4.37 mm. The published aluminum properties are 70.76 GPa and 2.7 gm/cm^3 for young's modulus and density. [10] They predict a bar velocity of 5119 m/s for a bare aluminum rod.

Typical ultrasonic signals in the bare aluminum rod and in the insulated aluminum rod are shown in Figures 5a and 5b respectively. In Figure 5a there is an initial small signal at about $20 \mu\text{s}$ and then a much larger signal starts near $30 \mu\text{s}$. In Figure 5b, the initial signal starts at about $25 \mu\text{s}$ and then a much larger signal starts about $35 \mu\text{s}$. In both figures, these signals are followed by additional signals that are either additional modes or reflections. Those signals overlap sufficiently to make identification difficult. In both figures, the second arriving mode clearly illustrates dispersive behavior with the higher frequencies traveling faster. Also, it can be noted that the bare aluminum rod has a much higher frequency content. The phase velocity of the axisymmetric mode of the bare rod and the polymer coated aluminum rod were measured to be $5119 \pm 26 \text{ m/s}$ and 4597

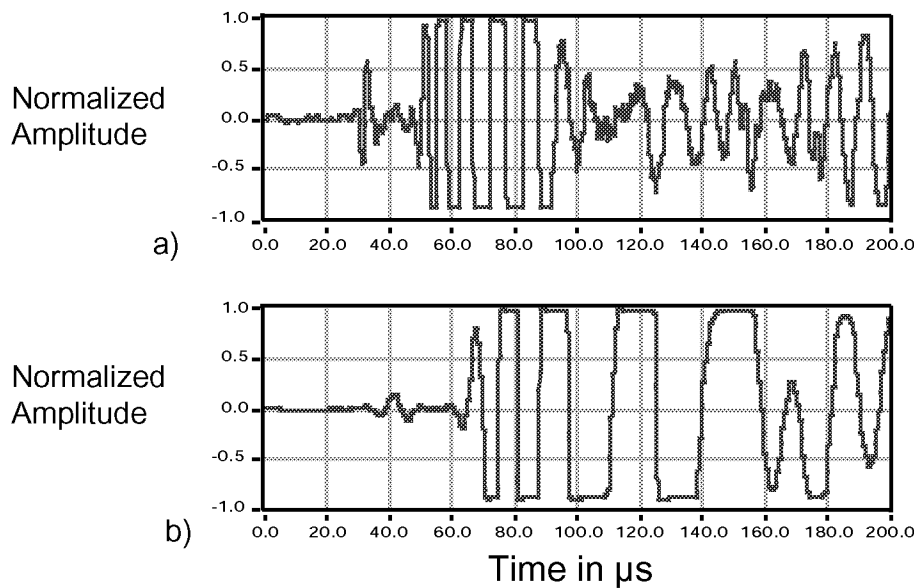


Figure 5: Typical ultrasonic signals. a) The signal generated and recorded from a 1/8" aluminum rod. b) The signal generated and recorded from a 1/8" aluminum rod with a layer of insulation

± 36 m/s respectively.

To see if this method might be applied to aging wiring, several mil-spec wire samples were heated to induce changes in the insulation. The samples were 12, 16, and 20 gauge MIL-W-81381 and MIL-W-22759/34 wires.

MIL-W-81381 Wire, Polyimide Insulation. Sets of twelve wires of MIL-W-81381 wire were heated to 370°C and held at that temperature for different dwell times and subsequently measured. This wiring had a listed maximum safe operating temperature of 200°C. In addition, a set of twelve wires that were not exposed to thermal degradation were used for baseline measurements. Visually, the wires darkened slightly with time in the oven, but did not display overt damage. Figure 6 shows the resulting ultrasonic data. The phase velocity for the 20-gauge MIL-W-81381/7 wire had a baseline value of 3023 ± 78 m/s. After exposure to the high temperatures, the wire's phase velocity rapidly increased, and reached an asymptotic value of 3598 ± 20 m/s after 100 hours exposure. Similar behavior was measured for the 16 gauge MIL-W-81381/21 wire and 12 gauge MIL-W-81381/12 wire which had baseline values of 3225 ± 22 m/s and 3403 ± 33 m/s respectively, and reached asymptotic values of 3668 ± 19 m/s, and 3679 ± 42 m/s respectively.

MIL-W-22759/34 Wires, E-TFE Insulation. Preliminary results on wires with a different insulation, a modified ethylene-tetrafluoroethylene plastic are presented in Figure 7. This aviation class of wiring is designated as MIL-W-22759/34 wire. This wiring had a listed maximum safe operating temperature of 150°C. Sets of twelve wires of MIL-W-22759/34 wire were heated to 270°C

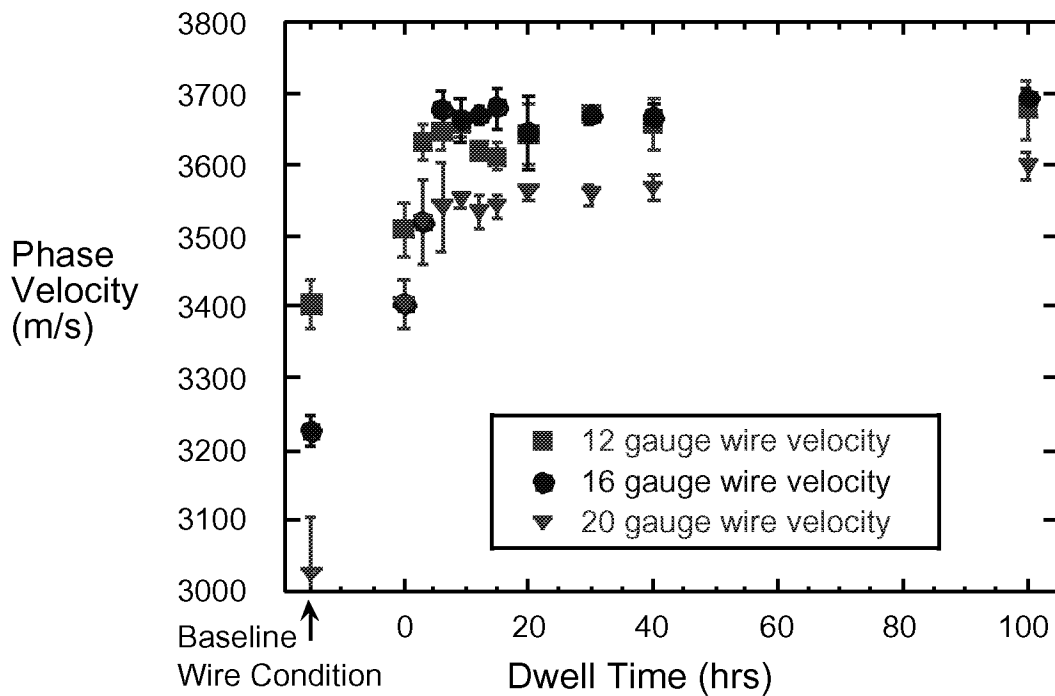


Figure 6: Ultrasonic axisymmetric phase velocity measurements on 12 (■), 16 (●), and 20 (▼) gauge polyimide insulated wire (MIL-W-81381).

and held at that temperature for different dwell times and subsequently measured. In addition, a set of twelve wires that were not exposed to thermal degradation were used for baseline measurements as before. Visually, the wires changed from white to brownish-gray color with increased darkening with time in the oven, but did not display overt damage. To date, the 20 gauge and 12 gauge wiring has been measured ultrasonically, and the data is shown in Figure 7. The phase velocity for the 20-gauge MIL-W-22759/34 wire had a baseline value of 2794 ± 21 m/s. After exposure to the elevated temperatures, the wire's phase velocity rapidly increased, and reached an asymptotic value of 3325 ± 17 m/s after 100 hours exposure. Similar behavior was measured for the 12 gauge MIL-W-22759/34 wire which had baseline values of 3430 ± 35 m/s and reached an asymptotic value of 3972 ± 61 m/s.

DISCUSSION

Figures 1 and 2 in the introduction predict some general properties for guided waves in clad and unclad cylinders. In the measurements that were made, the results correspond to those predictions. As seen in Figure 5, the axisymmetric wave arrives first and doesn't appear very dispersive, which is predicted for low frequencies. The flexural mode arrives next, and displays significant dispersive character with the lower frequencies traveling slower as predicted by the theory. In addition, the dispersive character shifts to lower frequencies for the clad rod because of the thicker diameter of the rod and insulation, which is also evident from Figures 1 and 2. The axi-

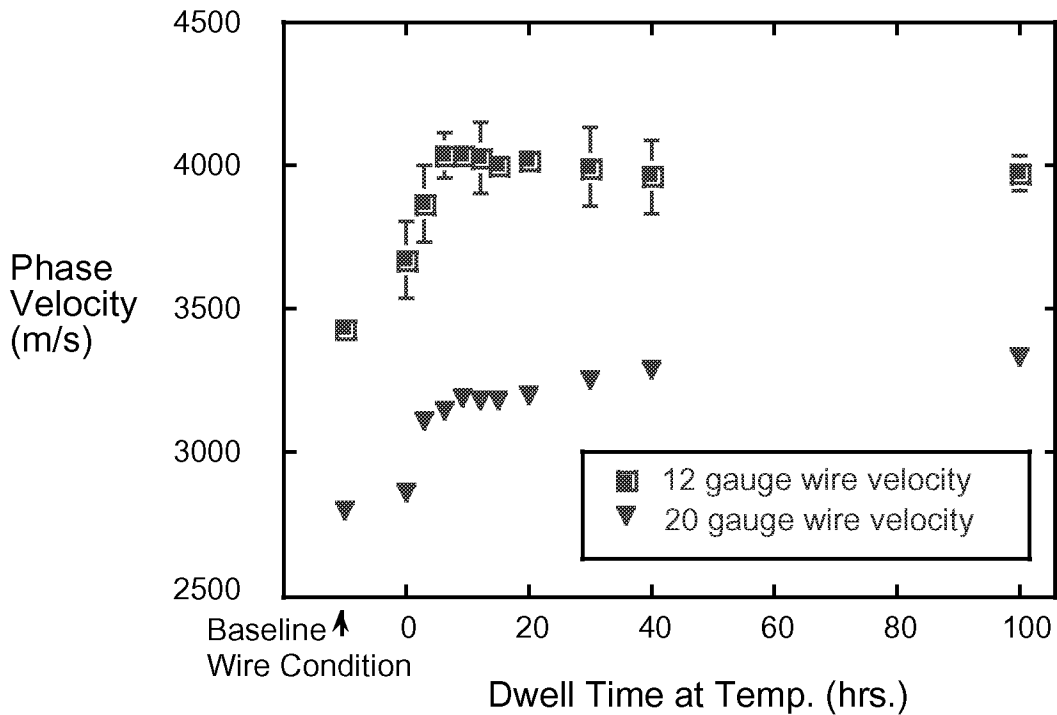


Figure 7: Ultrasonic axisymmetric phase velocity measurements on 12 (■) and 20 (▼) gauge E-TFE insulated wire (MIL-W-22795/34).

symmetric mode's velocity measurement in the unclad aluminum rod was within 0.2% of the calculated value based on published Young's modulus and density values for aluminum. Finally, the velocity of the axisymmetric wave and the flexural wave are significantly lower when comparing the low frequency unclad rod with the clad rod, which is evident in the waveforms in Figure 5. In the case of the unclad aluminum rod, measurements for the axisymmetric wave speed were 5119 m/s while for the clad aluminum rod, measurements of the axisymmetric wave speed were 4597 m/s, a 10% decrease. The difference in the measured values between the clad and unclad examples are similar to the qualitative behavior predicted in Figures 1 and 2. An important conclusion is that some of the ultrasonic energy is traveling in the insulation and can thus be used to evaluate the wire insulation condition. The relative signal strengths between the axisymmetric wave and the flexural wave is believed to result from the manner in which the ultrasound is generated (Figure 4).

In the case of the aviation grade wiring materials, high heat was used to try to produce a range of material properties in a rather short time frame, as naturally aged wiring with a well characterized history is not available at this time. Thermal "aging" is viewed as a way to make quick changes in material properties of wiring with some relevancy. Qualitatively, the measured ultrasonic rf waveforms for all the wiring materials used in this study were similar to those ultrasonic rf waveforms seen for the polymer clad solid rod, suggesting the applicability of the model to wiring despite the more complicated geometry of wire construction. Thus, it appears that the ultrasonic transmission

down concentric cylinders with intimate contact is a reasonably good model for the insulated wire, even with a stranded conductor and wrapped insulation.

The velocity behavior of each wire group to heat damage was generally similar. In all cases, the velocities increased between the baseline values and after the first heat cycle values, in both the MIL-W-81381 and MIL-W-22759/34 wire types and for all gauges tested. The general pattern was to increase monotonically. The measured velocity changes in the MIL-W-81381 wiring represented changes of 19, 14, and 8 percent respectively for the 20, 16, and 12 gauge wires. The measured velocity in the MIL-W-22759/34 wiring showed similar behavior with changes of 19 and 16 percent respectively for the 20 and 12 gauge wires. Both types of wires showed substantial changes in the velocity when exposed to excessive temperatures. Generally, by 20 hours exposure time, the velocities were within a few percent of their asymptotic values.

CONCLUSION

This work demonstrated the generation of ultrasonic axisymmetric and flexural guided waves in a clad and unclad aluminum solid rod and in insulated wire samples. Clip-on piezoelectric transducers were used to generate and detect ultrasonic guided cylindrical waves. A qualitative relationship with theory for cylindrical wave guides was demonstrated from the guided wave measurements on the unclad and clad aluminum rod. A qualitative similarity between our model and aviation grade wiring was seen. The axisymmetric wave mode was then measured for numerous samples of aviation wiring that had been subjected to extreme temperatures to help induce material changes in short time spans. The effects of thermal degradation were detected from the measurements of the guided wave speed in the MIL-W-81381 and MIL-W-22759/34 wiring in all gauges measured, showing easily detectable quantitative relationships between measurement and heat damaged wiring.

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